1949

Determination of oil film thickness in partial sleeve type bearings by electrical means

Shiflette, William Marshall

Annapolis, Maryland: U.S. Naval Postgraduate School

http://hdl.handle.net/10945/36328

DETERMINATION OF OIL FILM THICKNESS IN PARTIAL SLEEVE TYPE BEARINGS BY ELECTRICAL MEANS

William Marshall Shifflette

DETERMINATION OF OIL FILM THICKNESS IN PARTIAL SLEEVE TYPE BEARINGS BY ELECTRICAL MEANS

by

William Marshall Shiflette,
Lieutenant Commander, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Annapolis, Maryland
1949

This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING

from the
United States Naval Postgraduate School

[redacted]
Chairman
Department of Electrical Engineering

Approved:

[redacted]
Academic Dean

PREFACE

This investigation was performed at the United States Naval Engineering Experimental Station during the months of February and March, 1949.

While casting about in January for a suitable topic for investigation, Captain Liles W. Creighton generously offered the use of any of the station data and equipment which was fitted to the author's purpose. In talking to Mr. Watt V. Smith concerning current projects, the latter stated that some experimental attempts had been made at measuring electrically the film thicknesses in a bearing test machine and invited the author to further these investigations and enlarge upon them if desired. Thereupon this project was undertaken with the able assistance of Mr. Louis A. Nowell.

The author desires to express his appreciation to the above mentioned personnel of the Naval Engineering Experiment Station, and further to Mr. Mayo D. Hersey for his expert and friendly advice on lubrication matters, and to Mr. Gordon V. Schreitz for his cheerful and generous loans of equipment and instruments.

The author further desires to express his appreciation to Dr. Forrest K. Harris, Dr. C. Scott, and Mr. Wilbur Sze of the National Bureau of Standards for their advice and assistance in arriving at values of dielectric strength and dielectric constant of the oil.

Last, but by no means least, the author wishes to acknowledge the patient and friendly guidance of Professor C. V. O. Terwilliger during the conduct of the investigation.

Annapolis, Maryland
May, 1949

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

A Area, square inches

a $\frac{r'-r}{e} \simeq c/e$

C_b Capacitance of bearing, microfarads

C_{std} Capacitance of standard capacitor, microfarads

c Radial clearance

d Electrode diameter

E_b Breakdown voltage

E_{bo} Dielectric strength under standard conditions

e Eccentricity of journal

f Coefficient of friction

h Film thickness

h_m Minimum film thickness

h_1 Inlet film thickness

h_2 Outlet film thickness

K Dielectric constant

L Axial length of bearing

N Revolutions per minute

n Utilization factor of electrodes

O Journal center

O' Bearing center

P Transverse load on bearing

P'' Effective load per unit of projected shaft area with side leakage correction

p Geometric coefficient $\frac{r+S}{r}$

γ Geometric coefficient r'/r

R_b Resistance box resistance at bridge balance, ohms

R_{std} Resistance of standard resistor, ohms

r Shaft radius

r' Bearing radius

S Spacing between electrodes

α Angle from inlet to load line

β Angle subtended by effective bearing surface

θ Angle to any point on bearing measured from line of centers in direction of rotation

θ_1 Angle to inlet

θ_2 Angle to outlet

θ_1' Angle from minimum point to inlet

θ_2' Angle from minimum point to outlet

μ Absolute viscosity, reyns $\left(\frac{\text{lb-sec}}{\text{in}}\right)$

ϕ Angle from line of centers to load line

ψ Functional notation

CHAPTER I

INTRODUCTION

1. Summary

In this investigation an attempt has been made to measure the minimum oil film thickness in a partial sleeve type bearing under various conditions by two electrical methods; namely, by dielectric breakdown of the oil film, and by measuring the capacitance of the bearing and from this deriving the thickness of the film. Due regard has been had by the author for the limitations and capabilities of these methods and the results are propounded as largely qualitative in value; and to a lesser degree quantitative. The quantitative results have been checked by results as derived by classical hydrodynamic theory.

No complicated instrumentation was devised for this investigation in view of the indeterminate variable factors entering into the results, paramount of which was the tolerance of the machining involved.

The experimental results have proved to be fairly consistent from a comparison of the two methods, and the results of either method quite consistent with itself, particularly in the capacitance method. Where inconsistencies enter, the reasons for these have had an apparent answer in most cases.

The theoretical and experimental values of film thickness have agreed quite closely in the region from 50 to 125 microns, and sometimes higher, but in the region of thicker

films, above 200 microns, a consistent increasing divergence was observed. This confirms a divergence of actual film thickness from theoretical thicknesses reported by other investigators, and is on the same order of disagreement. This result suggests an inadequacy of such correction factors as the side leakage factor applied in theory.

Deliberate attempts were made to carry these investigations into the region of boundary lubrication in order to measure the lower limit of ideal fluid lubrication. This lower limit appeared to be on the order of 50 microns, in which region some anomolous effects were noted as evidenced by an apparent change in the dielectric properties of the oil film.

From a dielectric breakdown test of the oil used, it appears that the dielectric strength of the oil does not continue to increase with the decrease in electrode spacing, but tends to decrease after a certain minimum separation has been passed. Because of this uncertainty existing in necessary fundamental information, and because of a serious degree of physical deterioration of the bearing and journal surface as a result of arcing in the breakdown method, this method was found to be rather unsatisfactory for use.

The capacitance method was found to provide early warning of bearing failure prior to any physical evidence such as temperature rise and scoring, which suggested a practical use for such an arrangement in important naval and commercial applications.

2. Previous Work In This Field

Many men have worked upon the problem of determining film thicknesses in oil lubricated sleeve type bearings. Several methods of approach are offered. First there is the classical method of computation by means of hydrodynamic theory. Howarth (8) and Karelitz (10) among others have done considerable work in the field of theory. In the references noted much of their work is presented in graphical form. Norton (15) has adapted Howarth's work to other curves from which the theoretical thickness as well as angular position of the minimum oil film in partial sleeve type bearings may be determined. Norton's curves using the nomenclature of Figure 1 are reproduced in Figure 2 and are used as the means of determining the theoretical thickness for comparison with experimental results.

Under the realm of experimental determination by physical means we find several methods available. These include the general headings of optical, mechanical, electrical, electro-magnetic, and electro-mechanical. Under the heading of the purely electrical method come the methods used in this investigation; namely, capacitance and dielectric breakdown methods. Nucker (16) and Schering and Viewig (19) have done experimental work along this line by the capacitance method. Shering and Viewig have also done considerable work with resistance and dielectric breakdown methods. Poppinga (17) describes briefly the work of these men and shows some of their experimental methods and results. Kluge and

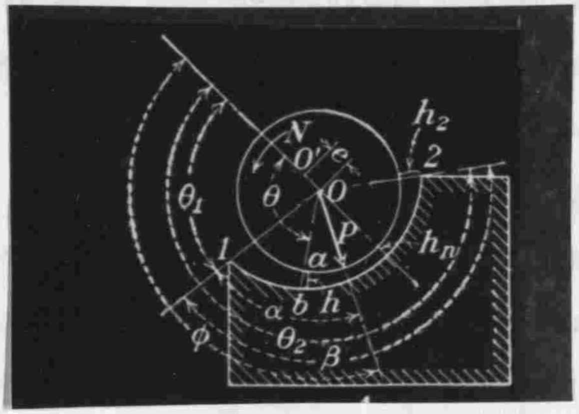


Figure 1 Diagram of a partial bearing

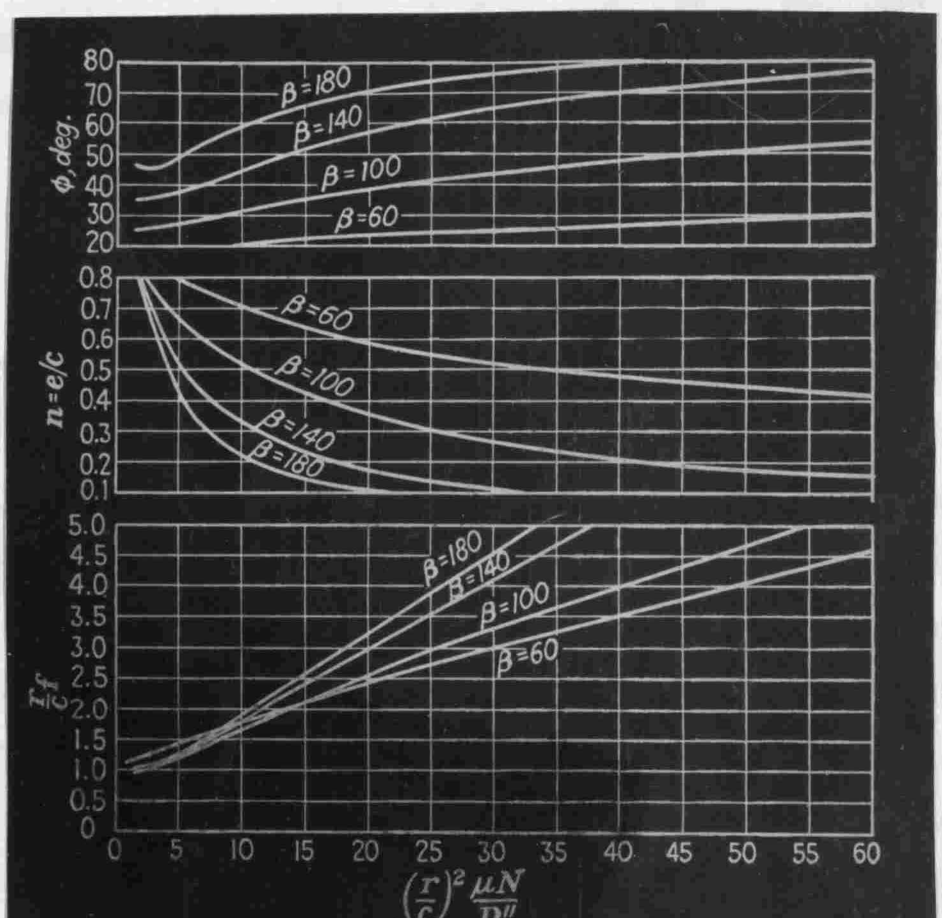


Figure 2
Characteristics of centrally loaded partial bearings

Linckh (11) have made investigations using the piezo-electric phenomena for determining journal position.

Allen (1) has done some of the most recent work using the dielectric strength method of determining film thickness. His principal sphere of interest was in the region from incipient to complete film breakdown, and he used instrumentation to provide indications of instantaneous film thickness, whereas this present investigation deals with average minimum film thickness. Allen found extremely wide disagreement between his experimental values and theoretical values. No such comparatively low values of breakdown potential were found to appear in the author's investigation as did Allen report. He furthermore used a fairly low value for dielectric strength without apparent justification, the readjustment of which would result in further disparity.

Several other men have engaged in work bordering on the field under discussion, and which is of intense interest in this case. Needs (14) made extensive investigations into the region of boundary film lubrication. He used mechanical means of determining the film thickness between two optically flat discs. He reported that when film thicknesses on the order of 100 microns were reached, the electrical resistance was very materially reduced, and at about 60 microns, extremely little resistance was offered to electrical currents.

Bruninghaus, Watson, and Menon conducted electrical measurements on extremely thin oil layers. They obtained for layers above 600 microns a resistance to penetration of over 250 KV/inch. In the case of thicknesses of less than 400

microns, Poppinga (17) reports that they were able to obtain penetration with much smaller voltages, indicating two-layer conduction by the oil film.

3. Description of Apparatus

Figure 3 shows a schematic drawing of the basic components of the test arrangement. Figures 4 and 5 show photographs of the arrangement.

The bearing test machine was manufactured by Alfred J. Amsler of Switzerland for dynamic bearing and journal tests. The speed was adjustable to a limit of approximately 375 R.P.M. Friction coefficients were easily obtainable from the known load imposed on the bearing by the spring and clamp mechanism shown in the photographs, and from the scale reading of a torque-arm which was displaced from its zero-speed nadir position by an amount corresponding to the frictional drag on the test journal. The machine was designed so that quick interchange of the journal and bearing could be made at will.

The journals used were mild steel, 1.25" in axial length and 2" in diameter. The surfaces had a Brinell hardness of 110 and a surface roughness of 4-6 microns R.M.S. by profilometer reading.

The bearings were machined on a special jig to clearances of .002" or .00475" on the radius. These bearings were 60° segment bearings 1" in axial length. Machining tolerances were ${}^{+.0002}_{-.0000}$ inches. The bearing metal, which was approximately 3/8" thick, was a tin base babbitt metal of the following composition:

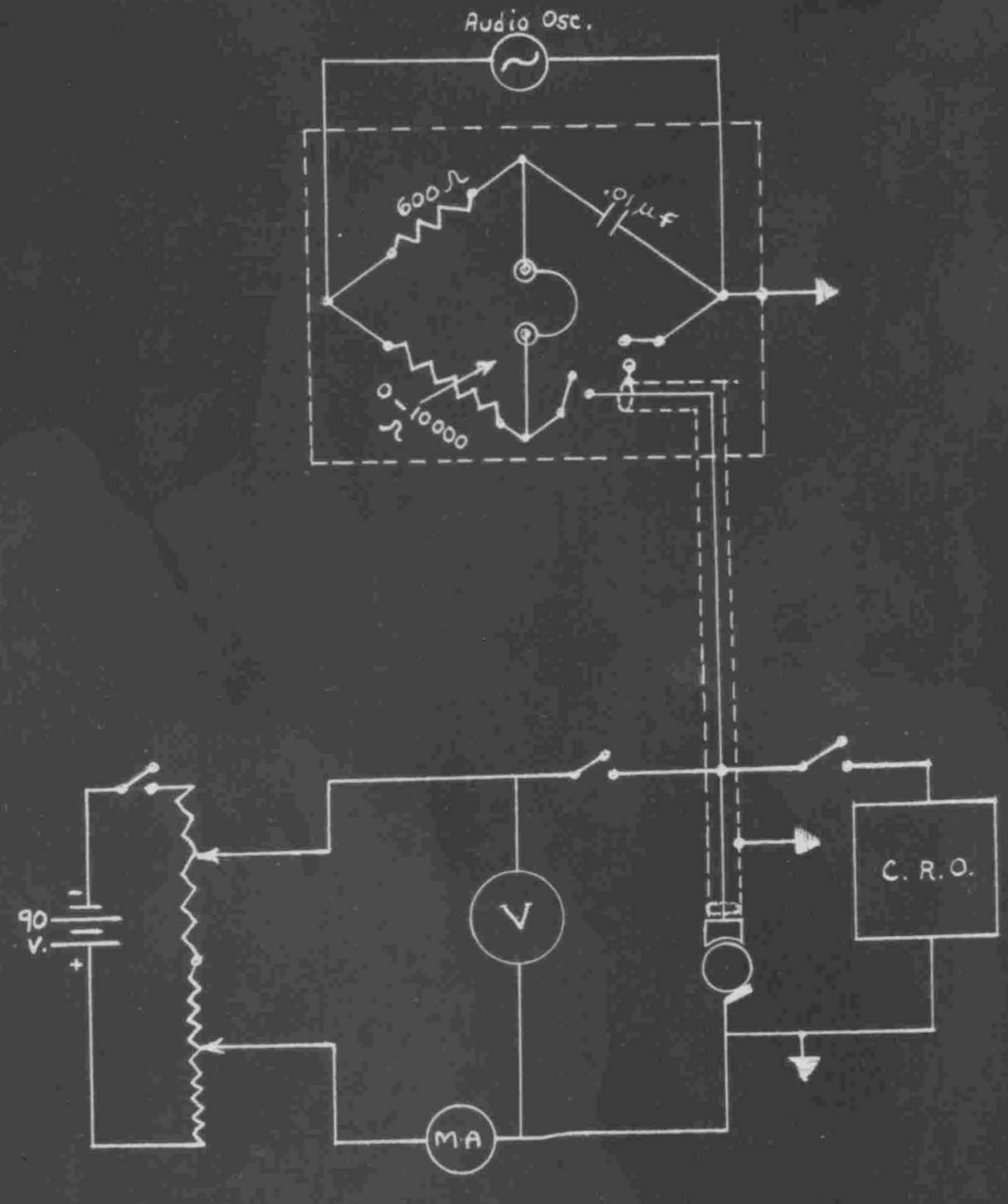


Figure 3. Schematic diagram of apparatus

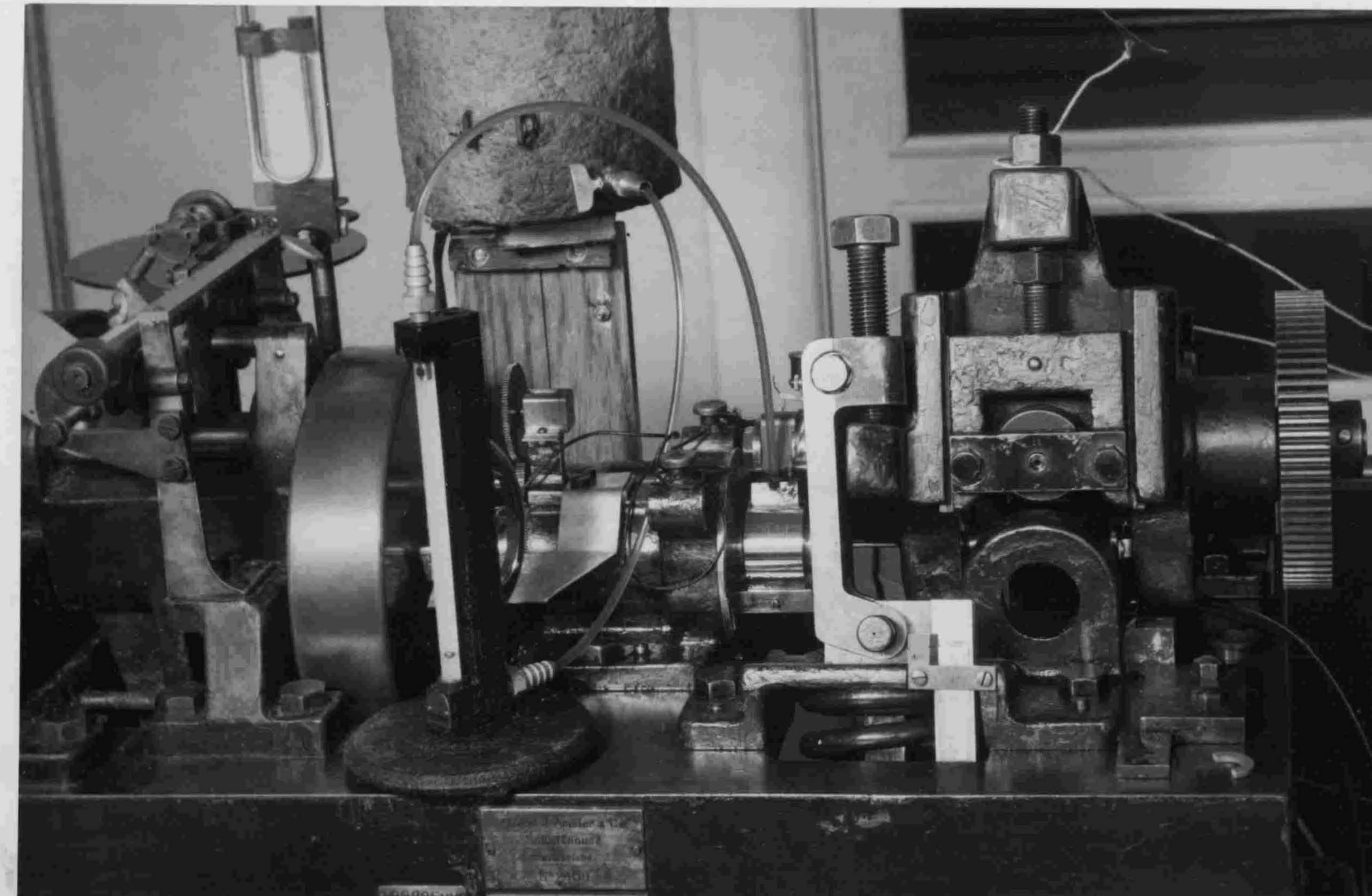


Figure 4 Mechanical detail of apparatus

Figure 5 Electrical detail of apparatus

tin	89%	copper	3.5%
antimony	7.5%	iron (max.)	.08%
lead	.35%	arsenic (max.)	.10%

Brinell hardness at 20°C-- 24.5
at 100°C-- 12.0

Melting point 466°F

Oil was supplied to the bearing through a transparent plastic tube from an insulated storage tank which was kept under sufficient air pressure (normally about 6 p.s.i.) to insure a complete oil film. Oil was distributed in the bearing by an axial slot near the leading (inlet) edge of the bearing.

The load on the bearing was applied centrally, that is, perpendicular to the shaft axis, through the geometric center of the bearing by means of a ball and spherical seat arrangement, thus allowing the bearing to be self adjusting. The ball was actually the spherical end of a short rod which was imbedded in a piece of phenolic material. The latter served to insulate the bearing from the rest of the machine. The arm to which the phenolic block was bolted could be pulled down by increasing the tension on a loading spring, thus increasing the load on the bearing as desired.

A flexible copper lead was soldered to the bearing for application of potential for dielectric breakdown and to enable connection to the capacitance bridge. The machine was grounded, as built, yet to insure positive contact with the journal one lead was installed on a copper rubbing strip rubbing on the shaft next to the journal.

A thermocouple lead was inserted in a radial hole in the bearing, terminating at a central axial position about three-quarters of the way toward the trailing edge, just outside the bearing surface. This lead was insulated from the bearing. Connection of this thermocouple to an electronic recorder provided a constant record of the oil film temperature. Initially a thermocouple was similarly installed in the distribution channel but no significant difference in the two temperatures was noted, hence the latter thermocouple was not reinstalled.

The dielectric breakdown setup was very simply instrumented as shown on Figure 3. "B" batteries connected in series furnished the potential through a course and fine potentiometer arrangement. Indication of breakdown was simply a large and sudden deflection of the milliammeter, at which time the voltage across the bearing would instantly collapse. In the current-voltage characteristic before breakdown, the relation approximates a straight line up until breakdown voltage is reached. The current up until this point is a matter of microamperes, although it may vary within wide relative limits owing to a large variation in the conductivity of oil. At breakdown the current increases very rapidly without further increase in voltage, and continues to increase with collapse in voltage. A typical voltage current relation from Gemant (3) is shown in Figure 6.
The maximum voltage reached before breakdown was the criterion of thickness found. A polar cathode-ray oscilloscope

was connected across the bearing as additional indication of breakdown.

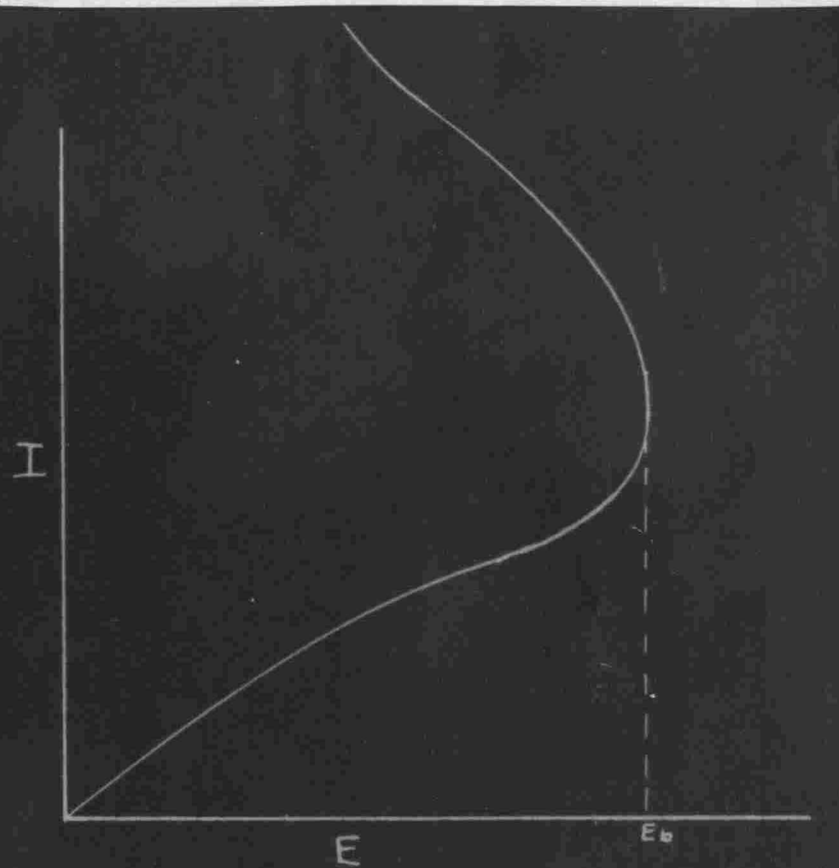


Figure 6. Current-voltage characteristic to breakdown in oil

The capacitance test arrangement was one which could be connected to the bearing by opening and closing two respective switches. A simple Wien bridge was used to measure the unknown capacitance. Potential was applied to the bridge by an audio-frequency oscillator, with earphones used to detect the minimum balance. Fair to good sensitivity can be achieved with this arrangement. To get complete zero potential balance, the voltages on the two legs must be matched in phase, in which case a galvanometer would be more sensitive. The dynamic stability of the journal was found to be

so poor that the determination of a minimum balance by means of the simple arrangement with the earphones was perfectly satisfactory. The bridge and all connecting leads were shielded to reduce stray capacitance. Best performance of the earphones was obtained at a frequency of 700-800 cycles per second impressed on the bridge.

4. Considerations With Regard to Methods Used

(a) Dielectric breakdown method. In this method the primary assumption is that the oil film will rupture at the thinnest point when rupture occurs. Given this assumption; it only remains to determine as accurately as possible the dielectric strength of the oil being used under the applicable physical conditions. This, unfortunately, the key to real success in this method, is most difficult to fix with precision and certainty. Dielectric strength is affected by the following factors, some of which we can regulate, others concerning which we must make certain convenient assumptions.

Chemical composition. This need not be known, but must be assumed homogeneous. The dielectric strength determined for one sample must hold for all other samples from the same source.

Impurities. These affect more than any other factor the consistency of the dielectric strength of the oil. Water is one of the most serious common impurities. The dielectric strength of the oil may be changed ten-fold very easily with minute quantities of water. Gemant (3), Miner (13), and Schwaiger and Sorensen (20) explain how minute quantities

of water as well as air and solid impurities seriously affect the dielectric strength of oils. These impurities will be assumed to be homogeneously distributed throughout all samples. By careful storage and handling, change in impurities during the conduct of the investigation should be eliminated.

Chemical changes. These include primarily such changes as oxidation, polymerization, and condensation reactions. The first is primarily a reaction with air, the latter two generally a result of, or hastened by high voltage stresses. All are rather long-time processes and will be assumed to have a negligible effect. Gemant (3) describes the nature of these processes and their effect.

Electrode spacing. This is perhaps the most important factor in pinning down the true value of dielectric strength and the one about which least is known in the region of extremely thin oil films. Many writers including Gemant (3), Miner (13), and Peek state that the dielectric strength varies inversely as the .4 or .5 power of the electrode spacing. This apparently does not hold, however, for very small spacings in oil of the order of a few hundred microns or less, for this rule results in absurdly high values of dielectric strength. Miner (13) gives another approximate relation which proves to be more consistent with observed facts. This relation is:

$$E_b = 177\sqrt{d}\,\log\left(1+\frac{S}{.76}\sqrt{d}\right)$$

where E_b is breakdown voltage in kilovolts
d is electrode diameter in inches
S is electrode spacing in inches.

This relation is quoted for spherical electrodes and does not exactly apply in our case. The best approach seems to be that of experimental determination of dielectric strength of the oil used, using electrodes geometrically similar, at a number of spacings approaching the smaller spacings expected as closely as practicable, then extrapolating the curve determined by this means.

Shape of the electrodes. This factor is known to have a marked effect on the breakdown potential as discussed by Miner (13), Gemant (3), and Schwaiger and Sorensen (20). Corona effects of sharp edges, ridges, or points decrease considerably the apparent dielectric strength. The surface shape or contour of the electrodes modify the concentration of the electrostatic field. Since all tests in this investigation were performed with the same shaped electrodes, that is; the bearing and shaft; at worst, the only effect of this factor would be to change the values of film thicknesses obtained from true to relative values, depending upon the similarity of the electrodes in the bearing machine and those used in determining the dielectric strength. Actually the electrodes in the standard dielectric strength test cup are flat 1" diameter discs which approximate the shape and area of the test bearing, but not the area of the journal used as one electrode.

Schwaiger and Sorensen (20) have gone into great detail

to determine the effect of variation of electrode shape upon puncture strength. They have computed values and constructed

graphs for determining the value of a factor n, defined as the utilization factor used in the relation

$$E_b = n S E_{bo}$$

where E_b is the potential required to cause breakdown between two electrodes with a given dielectric, S is the minimum separation, and E_{bo} is the dielectric strength of the dielectric used with flat plates at a standard separation. The utilization factor is always less than unity for non-homogeneous fields as found with adjacent cylinders, cylinders and planes, and partial planes with infinite planes. The utilization factor is a function solely of two geometric characteristics defined by the relative location and configuration of the two electrodes. The first of these geometric characteristics is p, defined by the radii of curvature of the two electrodes and the separation of the two. The other geometric coefficient, q, is simply the ratio of the two radii of curvature.

Thus, by carefully considering the applicability of the various utilization factors for geometrically similar systems, a working rule may be evolved for the effect of the unorthodox shape of the electrodes. It may be seen from study of the curves in the above reference that the utilization factor in our case approaches unity so closely that the electrodes may be considered parallel plates for all practical purposes.

Temperature and pressure. These factors have an appreciable effect, but, which may be minimized by regulation of the test conditions.

Time of application and rate of rise of potential. These also have appreciable effect, but by maintaining similar conditions in the investigation and in the test for dielectric strength, they need not cause any concern.

Frequency. The dielectric strength appears to decrease with increase in frequency. Miner (13) shows curves supporting this idea. It is evident that some error will be introduced by disregarding any change in dielectric strength due to minor frequency differences in test and reference conditions; but in any event, all measurements in the investigation should be conducted at one frequency and any error from non-standard frequency will be a relative error affecting all readings equally.

(b) Capacitance Method. In this method there is little or no difficulty in establishing a dependable value of dielectric constant to use in the relation

$$h_{ind} = \frac{2.54\,KA}{4\pi 9 \times 10^5 C}$$

where A is the effective capacitor area of the bearing and journal in square inches

C is the value of capacitance measured by some method, in microfarads.

The value of the dielectric constant varies somewhat with frequency, owing to a phenomenon known as anomalous dispersion; however, this does not appreciably affect the value of the dielectric constant in the range of 0-1000 cycles per second and may be here neglected.

Wide temperature and pressure changes also have appreciable effects upon the dielectric constant, but these effects may again be neglected within the variation of conditions to be expected in this investigation and those of standard test conditions. As an example of the variation in dielectric constant with temperature Poppinga (17) gives the values of the dielectric constant for an oil at $20^{\circ}C$ and $80^{\circ}C$ as 2.26 and 2.18 respectively.

One of the variables of which the capacitance is a function, hence also the measured film thickness, is the area of the condenser plates. The relation stated previously for finding the indicated thickness assumes flat parallel condenser plates of equal areas. In our case this is not true. There is a known area in the case of the test bearing, which is a 60° segment of a plain sleeve bearing. The effective area of the journal, the other plate, can only be estimated. Hoch (7) has measured the effect of various shapes and sizes of electrodes on capacitance corrections in precision work. The corrections for stray capacitance due to edge effect and electrode to ground field is a function of area and thickness of the electrode as well as separation of the electrodes. From this reference corrections can be arrived at but later it will be found that these corrections may be neglected in comparison with the values of measured capacitance since the corrections amount to approximately .3 of 1%. In view of this finding we shall use the actual area of the bearing surface as the capacitor area.

The separation of the two condenser plates is also a variable quantity. In the axial direction of the shaft, the separation will be considered constant. In the peripheral direction, the thickness of the film may be expected to decrease from the oil inlet side of the bearing to some minimum point, then increase again to the trailing edge. If the angular location of the minimum point can be determined and some relation found for the manner in which the thickness varies, values can be assigned the minimum thickness and a two-way integration performed to find the capacitance. Then, given the capacitor area and the computed capacitance corresponding to a given minimum film thickness, the "average" or "indicated" thickness may be then determined by solving the capacitance equation for h_{ind}. By performing a number of these integrations and computations for h_{ind}, a curve may be constructed from which the measured minimum film thickness can be determined by entering the curve with the parameter of the indicated average thickness computed from the measured capacitance. This is done later, as will be seen.

CHAPTER II

CONDUCT OF THE INVESTIGATION

1. Procedure in Obtaining Data

The oil used was 2190T turbine oil. Chemical tests showed this oil to be a predominantly napthenic base oil with no evidence of water or sediment present. The neutralization number was .06. The "T" designation indicates a polar additive in small amounts of less than 2%. The additive has a strong affinity for the metal surfaces, hence will displace any moisture and prevent oxidation or rusting.

It was decided to use more than one size of bearing; that is, more than one clearance. Journals were all 2" diameter but radial bearing clearances of .002" and .00475" were used. Various speeds and various loads were used. Some runs were made with constant speed, varying loads, and others vice versa. Speeds were decreased and loads increased until mechanical film breakdown was in the incipient stage.

New bearings and journals were run in for several hours before the test readings were begun. The sequence of the runs was randomized insofar as practicable to minimize any extraneous effects causing changing physical conditions. One example of such effects was an apparent surface roughening growing progressively worse as the number of arc-overs from dielectric breakdown increased.

At each new setting of speed or load, a short delay period was necessitated in order that a condition of thermal equilibrium was reached. This was indicated by a constant

reading of the oil film thermocouple. This delay was normally on the order of about five minutes.

The theoretical film thickness is determined from the relation

$$h = \psi \left[\left(\frac{r}{c}\right)^2 \frac{\mu N}{P''} \right]$$

For each experimental reading, then, it was necessary to know the radius of the journal, the clearance, the absolute viscosity of the oil in the bearing, the speed, and the load on the bearing in order to compare with theory. The first two remain constants for any set-up. The viscosity was determined from the temperature of the oil film as measured by the thermocouple previously described. The speed was simply obtained by mechanical counter. The bearing load or pressure was determined from the deflection of the loading spring.

In addition to these readings, the friction factor was determined for each run, as was the rate of oil flow.

In measuring the voltage to breakdown a procedure closely approximating the standard short-time test as described by Miner (13) was followed. This, briefly, consisted of a slow but steady increase in the potential applied across the bearing. The rate of rise of potential was as rapid as could be used without causing inertia carry-over to enter into the voltmeter reading. The maximum voltage reading obtained was the thickness criterion. Usually several breakdowns were made at each setting in order to check for consistency of results. Frequently, the same conditions would

be imposed on the test arrangement as for some previous run to ascertain whether or not the previous results could be duplicated.

The measured film thickness indicated by the breakdown test was arrived at simply by dividing the potential necessary to cause breakdown by the best value of dielectric strength for the estimated separation, arrived at as described in the next section.

The capacitance measurement was accomplished by connecting the bearing and journal as the unknown capacitance in the Wien bridge, applying a.-c. potential to the ends of the bridge, then arriving at the reading of the variable resistance to give the minimum sound level in the earphones. In order to get maximum clearness and distinguish the applied frequency hum in the earphones from background noise, the frequency was rocked back and forth by adjusting the oscillator while arriving at a balance. The voltage impressed on the ends of the bridge was also varied to give best results, the potential best suited depending upon the background noise level. Normally a voltage of 3-8 volts was adequate.

The relation of the capacitance bridge is

$$\frac{R_b}{R_{std}} = \frac{C_{std}}{C_b}$$

or

$$C_b = \frac{C_{std} R_{std}}{R_b}$$

which in the case of the values used, resulted in

$$C_b = \frac{.01 \times 600}{R_b} = \frac{6}{R_b} \text{ microfarads.}$$

Then using known values of the dielectric constant, K, and the area of the plates we arrive at the indicated thickness of the film by the relation

$$h_{ind} = \frac{2.54 \, K \, A \, R_b}{4\pi \, 9 \times 10^5 \times 6} \quad \text{(inches)}$$

It has been previously explained in section I-4(b) how the relation between the minimum film thickness and the indicated average may be arrived at by computation and graphical means. The necessary computations and the graphical relations arrived at are included as Appendix C.

2. Determination of Dielectric Strength and Dielectric Constant.

(a) Dielectric strength values were arrived at from the curves in Appendix B which show the relation between electrode spacing and dielectric strength for the oil used. Owing to the very small values of electrode spacing involved in this investigation, extrapolation of the curves was necessary, which is, of course, a dangerous procedure, but unavoidable. Two plots are shown for mutual check; one linear, the other logarithmic.

The dielectric breakdown tests were made following the short-time test procedure outlined by Miner (13) and A.S.T.M. Standard D-117, and using the standard test cup described in

those references. These tests were made using Bureau of Standards equipment and with the assistance and advice of their personnel. The test frequency was 60 cycles.

Spacing of the electrodes at separations below the standard .1 inch separation was gauged by means of feeler gauges. These spacings were reset frequently to avoid error in any one setting. As shown by the curves in Appendix B, the average values of breakdown for each cup of oil are plotted, with the curves drawn through the average value of breakdown for each spacing.

A value of 275 KV per inch was the value of dielectric strength actually used in computing the values of film thickness. This is purely an arbitrary value based on the extrapolation of the curves of Appendix B, and on the known fact that the dielectric strength for direct potential is somewhat less than the peak values of low frequency alternating voltages. The other factor which influenced this decision is that the rate of voltage application in this investigation was somewhat slower than that used in the standard test, which factor tends to lower the value of dielectric strength to be used.

(b) The dielectric constant of the oil was determined by the National Bureau of Standards at 25°C and 1000 cycles per second in a Balsbaugh 3-terminal cell. The value found was 2.283 $\pm$ .001 and was the average of three measurements.

3. Determination of Theoretical Values of Film Thickness

As stated before, the thickness of the oil film is a

function of the journal radius, bearing clearance, viscosity of the oil, the speed of the shaft, and the pressure on the bearing. One other factor had also to be considered in determining the theoretical film thickness. This factor was side leakage of oil from the bearing. On a bearing in which the axial length of bearing surface is very long in relation to the length of bearing in the direction of relative motion, this factor may be neglected, but in the case of narrow bearings the side leakage may reduce the film thickness to a much smaller value than it would be otherwise. This effect may be accounted for by utilizing a factor such as

$$\frac{P}{P_\infty}$$

which we will call the side leakage factor and which may be defined as the ratio of the pressure on a bearing with a certain minimum film thickness and given finite bearing width, to that pressure on the bearing with the same film thickness, and an infinite bearing width.

Norton (15) gives values for this side leakage factor plotted against the ratio of bearing length in direction of motion to axial length. In our case, with the reference ratio approximately equal to unity, we find a side leakage factor of .45. This factor must be divided into the apparent load as determined from the loading spring deflection to arrive at the effective load on the bearing.

Attention is called to the fact that the factor P" is the effective force per unit of projected area of the shaft,

not the bearing segment. Thus,

$$P'' = \frac{P}{2rL\ .45}$$

With all factors now determined, the theoretical values of film thickness were simply determined by entering the curves of Figure 2 with the value of the abscissa. At the same time the theoretical angular locations of the minimum points were determined for later use in capacitance calculations. It should be noted that the values of ϕ read from the upper curve are the supplement of the angle ϕ shown in Figure 1.

CHAPTER III

EVALUATION OF RESULTS

1. Comparison of Experimental and Theoretical Results

Tables 1, 2, and 3 of Appendix A show the summation of data taken with the resultant values of h_n, along with the corresponding theoretical values of h_n. Figures 7, 8, and 9 show these comparative values of experimental and theoretical film thicknesses plotted for ease in comparison. The numbers 1, 2, or 3 on the curves represent the order in which listed on the applicable table and also shows the chronological order in which data were obtained.

Figure 7 shows the results of two runs with a radial clearance of .002", holding speed constant. At the start, a new journal was being worn in. It should be noted, to begin with, that perfect methods would result in all four experimental curves being coincident on one line, not necessarily agreeing with the theoretical line. In other words, for any one value of the abscissa, all measured film thicknesses should be identical. Not shown because of scale limitations, but tabulated in Table 1, is evidence of very close agreement between the two experimental methods at a value of 41 for the Sommerfeld Variable. This agreement appears fair all along. Values determined by the capacitance method show good consistency with each other, the dielectric breakdown values less so. The fact that run 2 was made at a lower speed than 1 has no bearing on the fact that the values of

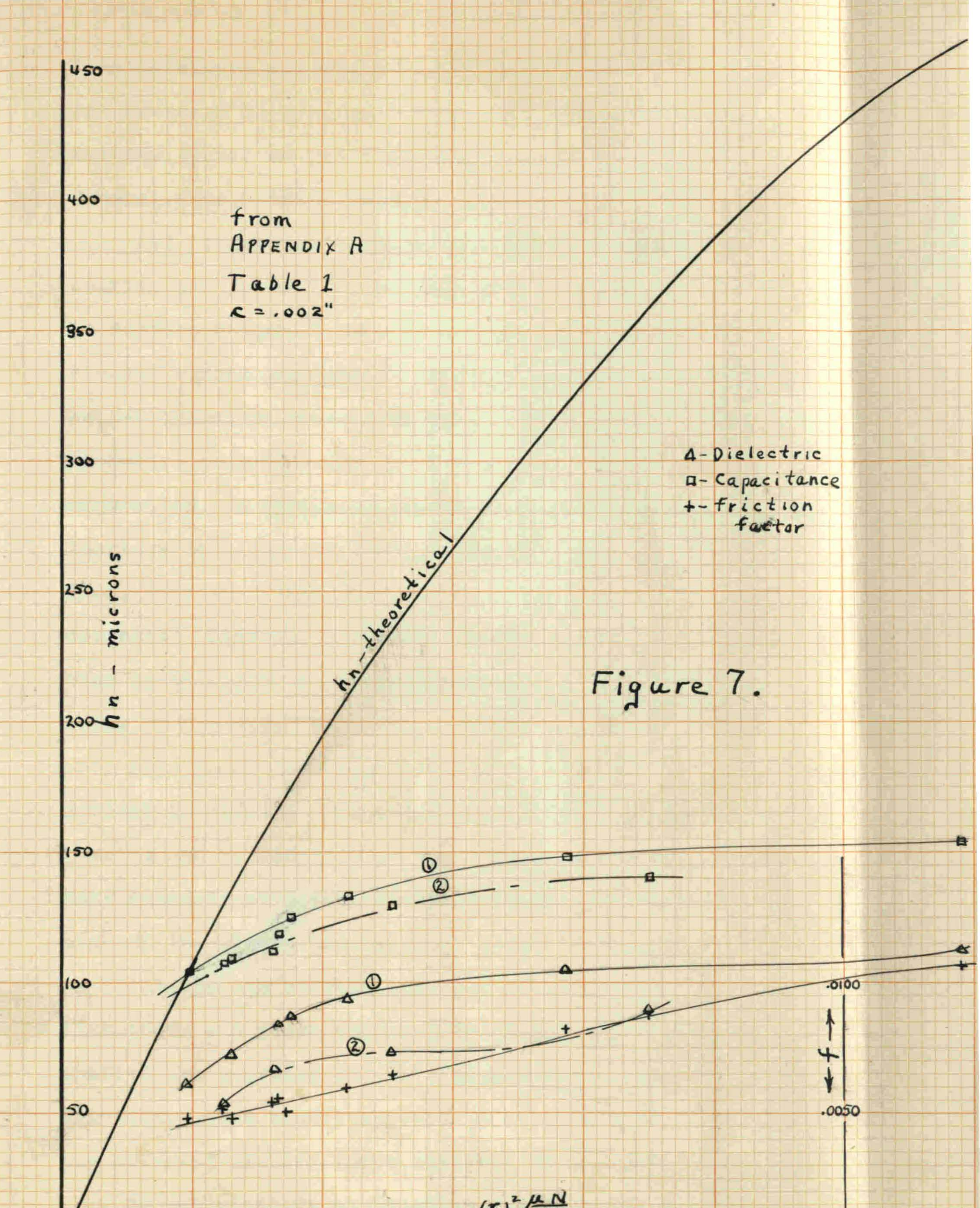

from
APPENDIX A
Table 1
c = .002"
Δ- Dielectric
□- Capacitance
+- friction factor
hn-theoretical
hn - microns
450
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
$\left(\frac{r}{c}\right)^2 \frac{\mu N}{P''}$
.0100
.0050
f
①
②

Figure 7.

film thickness are consistently lower for run 2. This apparent decrease in thickness from run to run was noted throughout the course of the investigation and can be explained in several ways. These theories are, in order of acceptability:

(a) There was a progressive surface roughening of both bearing and journal in the way of the arcing. The changes in surface roughness were measured by profilometer. The increased number and heights of sharp peaks on the surfaces caused increased concentration of electrostatic stresses, therefore a lower value of dielectric strength for the same separation. A change in capacitance also resulted from an increase in effective surface area of the capacitor plates. Thus, increased area resulted in increased capacitance and decreased apparent thickness, but to a lesser degree of change than in the case of the dielectric breakdown measurement owing to the localized effect on the capacitor area.

(b) Polar molecules of the additive or of a heavy polymerization product gradually adhered to the surfaces of the bearing and journal, orienting themselves in layer upon layer, many hundreds of molecules thick, until the effective separation of the plates became very appreciably less.

(c) As the bearing and journal gradually wore in, the high spots and rough points were slowly worn down which enabled the surfaces to run closer together with ideal fluid friction. This theory appears quite unacceptable in view of the observed pitting which occurred as a result of arcing.

No satisfactory explanation can be given for the wide

diversity of the theoretical and experimental values of film thickness with increase in value of the Sommerfeld Variable. It seems probable that a constant value for the side leakage factor is not adequate as the film thickness increases several fold. The same trend of disagreement between theory and experiment was found by Howarth, shown in Norton (15).

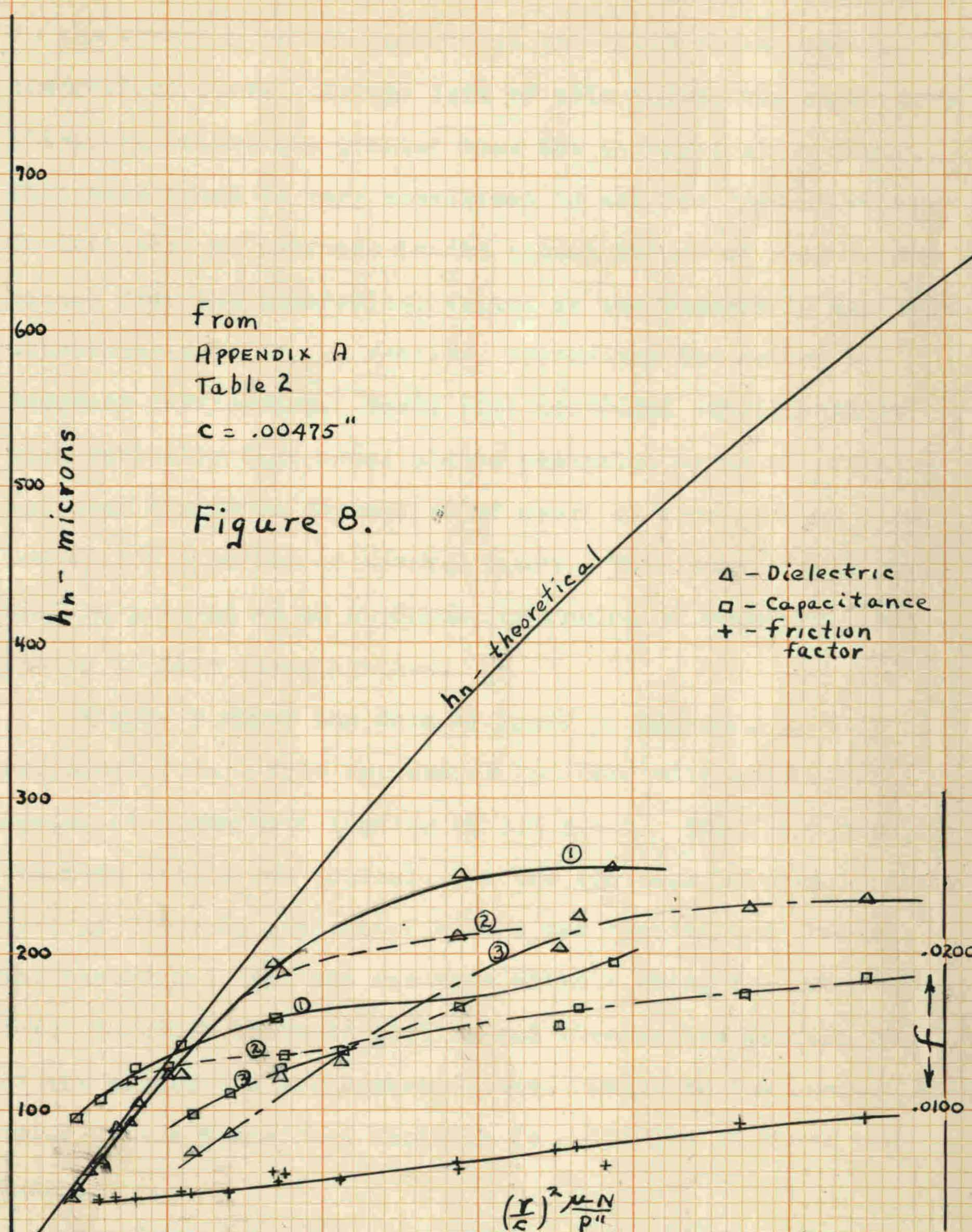
The values of the film thickness by breakdown ran consistently at about 50 to 75% of the values by capacitance method in Figure 7. This relation was found to be reversed in later runs, in general. The lower breakdown values in the first two runs are probably due to unpredictable and unusual stress concentrations in the first bearing caused by previous pitting and by the edge effect of a particularly sharp edge of the bearing or oil distribution slot.

In Figure 7 the theoretical values, and the experimental values by capacitance are seen to come into agreement in the neighborhood of 100 microns. The minimum value of film thickness before mechanical breakdown is indicated as between 50 and 100 microns. At this point the film no longer exhibits normal dieclectric properties. It is not known whether the film suddenly loses its dielectric properties and becomes conducting as has been theorized by some writers on the subject, or whether enough high points on the bearing and journal surfaces enter the region of so-called boundary lubrication to give the effect of metal to metal contact. In boundary lubrication only an extremely thin molecular layer separates the surfaces involved and those molecular layers are believed to adhere closely to the surfaces of the metal, so oriented

as to produce two-layer conduction.

Figure 8 shows the graphical representation of the data from Table 2 of Appendix A. This constitutes three consecutive runs with a new bearing of radial clearance .00475" but the same journal as used in the runs of Figure 7. The first two runs were made at constant speeds of 362 and 193 r.p.m. respectively. The third run was made with a constant load of 116 pounds per square inch effective loading per square inch of projected journal area. The capacitive film thicknesses shown in Figure 8 exhibit a trend very similar to those in Figure 7; in fact, the actual values are not far different, being slightly greater in the case of the greater radial clearance as might be expected.

The values of the film thicknesses by breakdown methods in Figure 8 are seen to be greater, in general, than those found by the capacitance method; quite the reverse of the case in Figure 7. Very good agreement with theory resulted up to a thickness of 200 microns. This happens to be at about the same value of the Sommerfeld Variable that agreement was found in Figure 7. The apparent reason for the greater relative values of breakdown thicknesses is that a new bearing was installed at the start of this series. Since no pitting was present at first, no stress concentrations were introduced to give apparently smaller values of film thicknesses. The cumulative effect of pitting on the experimental values found is clearly demonstrated in Figure 8 by the constant trend downward of the successive runs. Run 3 shows a marked decrease in apparent thickness by breakdown method at the lower values of the Sommerfeld Variable.


From
Appendix A
Table 2
c = .00475"
Figure 8.
h_n - microns
700
600
500
400
300
200
100
.5
1.0
1.5
2.0
2.5
3.0
$\left(\frac{r}{c}\right)^2 \frac{\mu N}{P''}$
h_n - theoretical
Δ - Dielectric
□ - Capacitance
+ - friction factor
.0200
.0100
f
①
②
③

Here again, in Figure 8, we find the minimum measured film thickness between 50 and 100 microns.

An item worthy of notice, but which cannot be explained, is the crossing of the capacitive thickness curve over the theoretical curve. To the left of this point, the capacitive thickness values are greater than the theoretical values. This same trend is very consistent in all the figures shown. It indicates an increase in the actual values of film thicknesses over the theoretical values as the Sommerfeld Variable approaches zero or, in reality, approaches the region of boundary lubrication. Needs (14) has found experimentally that optically flat metal plates separated by an oil film approach a minimum separation of about 40 microns even when loaded for a period of several hours. This same effect may well be present as we approach the region of boundary lubrication in this investigation.

Figure 9 shows the data of Table 3, Appendix A, in graphical form. This represents two runs with $c = .00475''$ again, at a constant loading of 338 p.s.i. The first run was made with a new journal, but the old bearing used in the runs of Table 2; the second with a new bearing and journal. The second and last run was made without using the breakdown setup in order to avoid pitting and observe the performance of the capacitive arrangement alone. Owing to the load, the value of the Sommerfeld Variable is quite low in these two runs.

Little new is to be gleaned from the inspection of

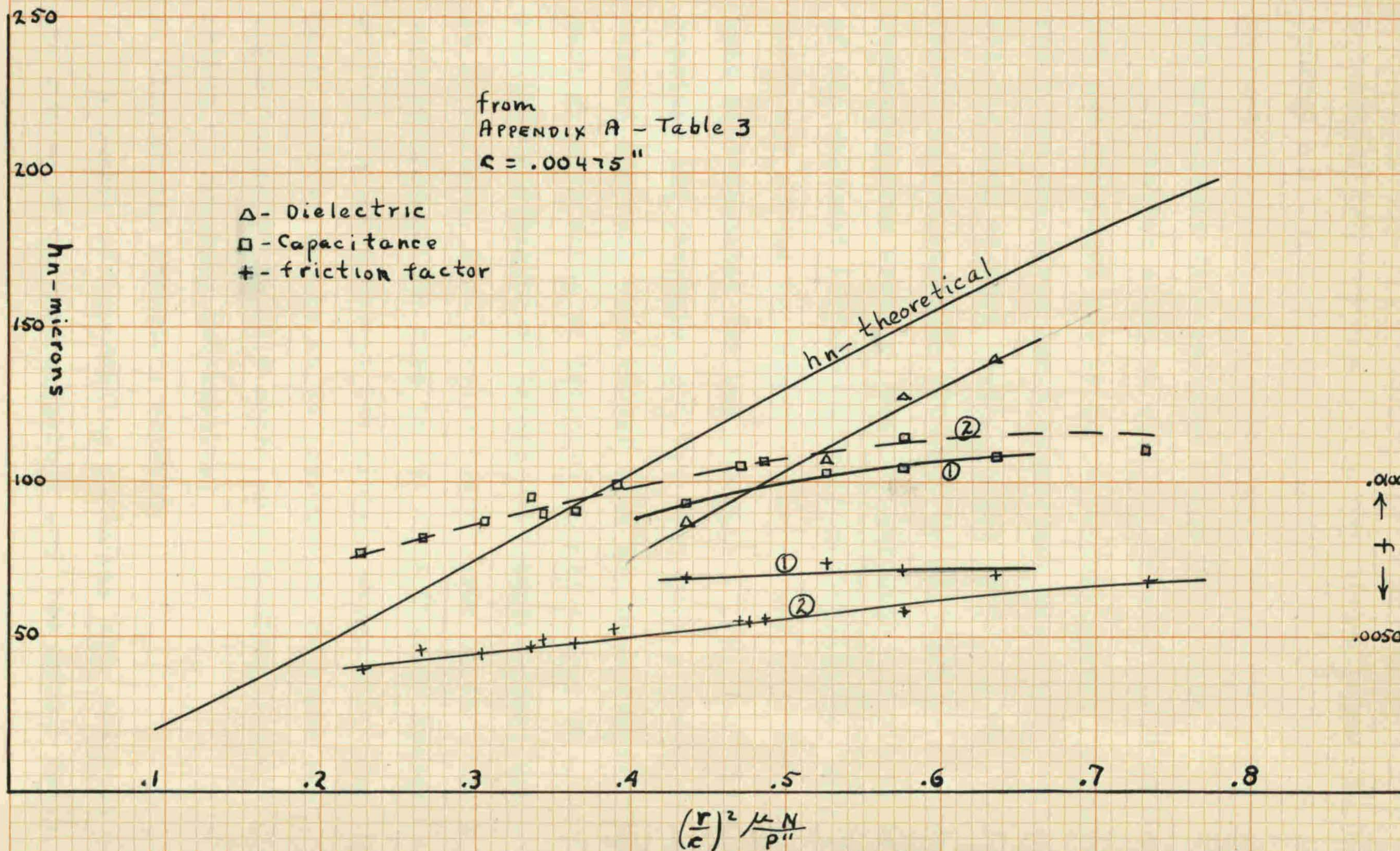

from
APPENDIX A - Table 3
c = .00475"
Δ - Dielectric
□ - Capacitance
+ - friction factor
hn - theoretical
hn - microns
250
200
150
100
50
.1
.2
.3
.4
.5
.6
.7
.8
.0100
f
.0050
①
②
①
②
(r/c)² μN/P"

Figure 9.

Figure 9. The capacitive value of thickness is seen to show a relative increase again with the installation of the new journal and bearing. The capacitive curve again crosses the theoretical curve at approximately 100 microns, with the minimum measurable film thickness some 75 microns.

A function shown on each figure with the film thicknesses, but not discussed yet is the friction factor. On Figures 7, and 8 the one curve for f represents the composite curve for all the runs on that sheet. These show that the friction factor is not markedly affected by the surface roughening resulting from arcing. This is somewhat surprising in view of the measured increase in surface roughness. Only Figure 9 shows any change in friction factor, but here this change must be discounted for the two curves represent different bearings and journals, and the fact that a new unpitted bearing and journal, even though with the same nominal dimensions, gave a lower value of friction factor cannot be accepted as conclusive evidence of friction increase caused by pitting. It is certain, from previous experience in this field, that continuation of the runs in the direction of decreasing Sommerfeld Variable beyond the minimum measurable film thickness would shortly result in an increase in friction factor, showing a "knuckle" in this curve corresponding closely to the region of boundary lubrication.

2. Incidental Phenomena Observed

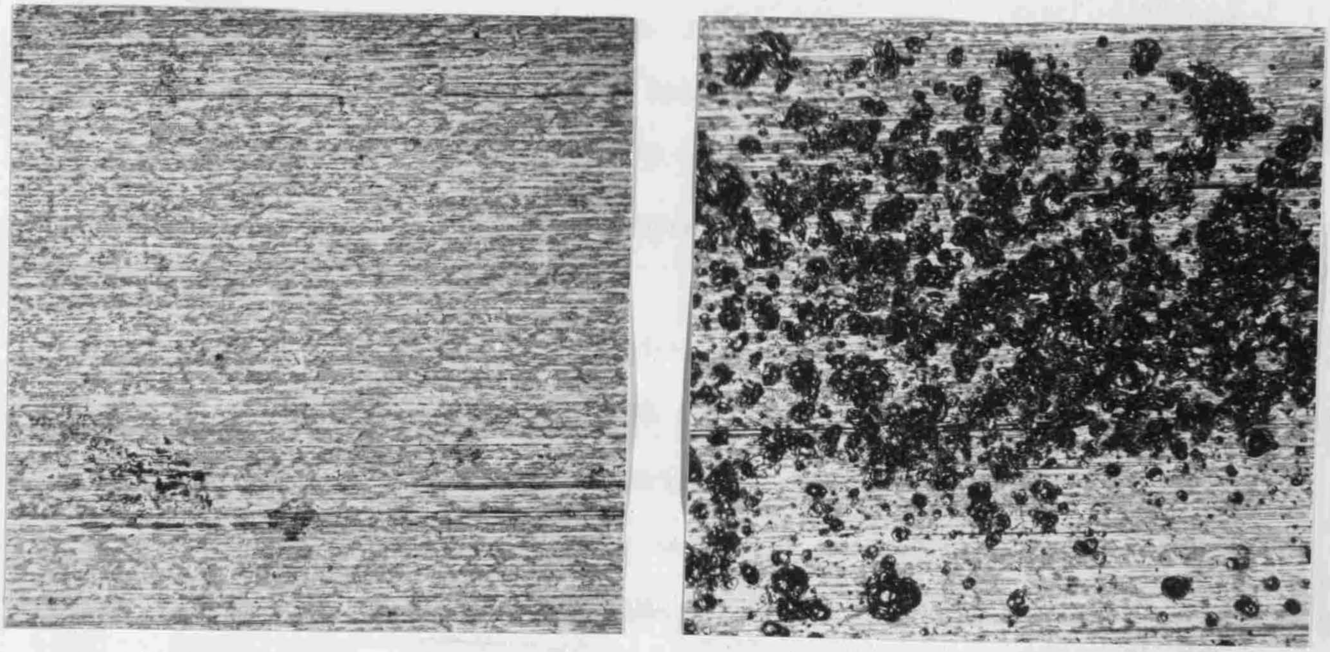
A number of interesting phenomena were observed during the course of the investigation that the author feels are

worthy of comment. The first of these, which has already been covered to some extent previously, is pitting. This surface roughening has been called pitting, but in reality, there may also have been a considerable amount of actual metal deposition which would result in the same effect. This would be expected from the welding process present for the short periods of arcing. The high arc temperatures undoubtedly caused some local melting of the bearing metal with its melting point of only 466°F, and probably some in the journal metal with its melting temperature of around 2000°F. The polarity was purposely arranged as shown in Figure 3 since it was felt that less destructive pitting would occur with this arrangement in view of the cell known arc-light principle that the hottest point and an actual depression occurs in the positive electrode.

The heights of the surface rough points resulting from the arcing is of interest in order to correlate these in a rough way with the apparent relative decrease in film thickness with progressive surface roughening. The original journal surface had a surface roughness of 2-4 microns, root mean square, as measured by profilometer. According to Tarasov (22) this corresponds to a predominant peak to valley height of 9-18 microns. After considerable arcing, the surface roughness measured by the same means increased to 10-15 microns, r.m.s., which corresponds to predominant peak to valley heights of 45-67 microns. Photomicrographs of journal and bearing surfaces are shown on Figure 10 to illustrate the

RMS 2-4
Before Arcing

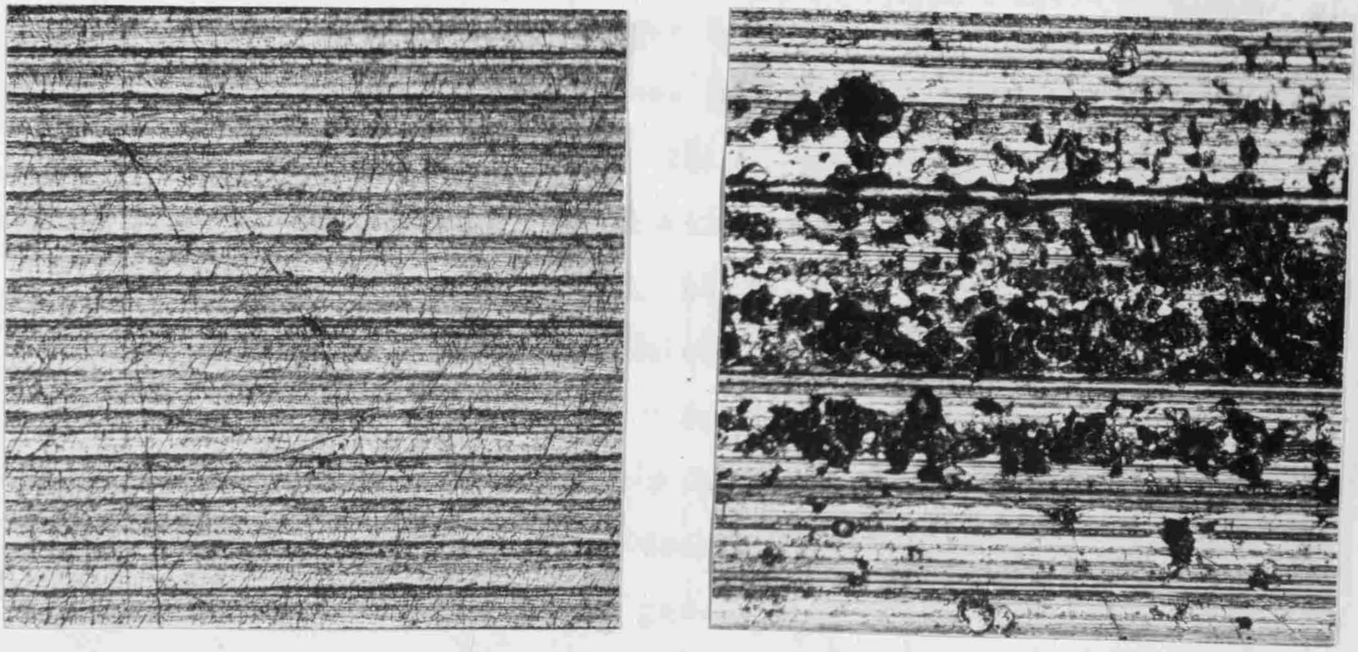
RMS 10-15
After Arcing



110 BHN Steel Journal
X 100

Before Arcing

After Arcing



Tin Base Babbitt Bearing

Serial No. EES C-3230

Figure 10. Photomicrographs of journal and bearing before and after arc damage.

appearances of these surfaces before and after arc damage. The type of pitting shown occurred generally over the journal in the path of the bearing. On the bearing the surface roughening or pitting occurred toward the trailing edge where the minimum film thickness was expected, covering perhaps 25% of the bearing surface.

The second item of the phenomena was the audible effects in the bridge earphones caused by various friction conditions in the bearing. When a new bearing or journal was first installed, it was impossible to obtain readings of film thickness by either electrical means with any moderate or heavy bearing loads. Absence of dielectric film was indicated. Then as the bearing was worn in, the film began to show signs of having appreciable thickness. The capacitance bridge could shortly be adjusted to a minimum balance with a great deal of low beat frequency noise in the background, the beat frequency usually being somewhere between the speed of the shaft and the frequency of the oscillator. This indicated multiple high spots on the bearing or shaft which were subject to erratic and intermittent contact with the opposing surface. Occasionally a clear cut case of one markedly high spot on the journal would manifest itself. Each time the high spot passed over the bearing surface, contact or near contact resulted and a high intensity beat would be heard in the earphones during the time of the high point's passing over the bearing. The frequency of this beat would be exactly that of the shaft speed.

As the bearing became more and more worn in, little or no background noise was apparent. With a well worn in bearing and light loads, a very clear tone resulted in the earphones and a fairly low minimum balance could be obtained with the bridge.

An occasional piece of foreign matter would enter with the oil stream and be instantly detected if the bridge were adjusted to or near balance. Whether the foreign matter attached itself to the bearing surface or the journal was faithfully reported by the earphones; either a constant howl or a staccato note was the answer.

Interruption of the oil supply was tried. It was found that breakdown usually occurred, as indicated by a mounting crescendo in the earphones, within 7-10 seconds. This audible alarm was apparent before any appreciable temperature rise occurred in the oil film and before any scoring resulted. Another method of audible detection of bearing trouble was used in the investigation. In place of using earphones across the bridge, the potential was applied to the grid of the detector stage of a small radio receiver. After suitable volume adjustment, any unbalance of the bridge, indicating bearing trouble, was instantly reported through the audio stage and speaker.

The third item of phenomena concerns the use of the cathode ray oscilloscope. No mention of the c.r.o. has been made in evaluating results so far since no clear-cut or decisive intelligence was furnished by this device using d.-c.

potential for breakdown. Some experimental runs were made with a.c., however, in which case the c.r.o. was very useful in supplying information. The oscilloscope was of the polar type with a dot tracing a circle around the center synchronized with the speed of the shaft. Application of an alternating potential to the probe terminals of the oscilloscope resulted in the circle becoming a sine wave traveling along the circular path. When the oscilloscope was installed across the bearing with an a.-c. potential being applied to the bearing; the scope clearly showed when intermittent and incipient breakdown occurred by a very ragged appearance of the sine wave, and when complete breakdown occurred, by a complete collapse of the sine wave to the circular path again. The existence of a high point on the journal was clearly indicated by the repetitive collapse of the sine wave at one fixed spot. High spots on the bearing were indicated by frequent collapsing of random parts of the sine wave.

The fourth phenomenon to be mentioned concerns the effect of high voltage stresses in forming a true fluid film in the bearing. Frequently during the course of the investigation it was found that upon adjusting the apparatus to a heavier load or lighter speed boundary lubrication was apparently present; at any rate breakdown was indicated by the highly conductive nature of the film. Then upon the application of a rather high potential across the bearing, sometimes once, sometimes several times, a fluid film would be

brought about and indicated with normal dielectric properties. This behavior may have been the result of the presence of an additive in the oil. Although the agent is not identified, being a proprietary substance, it may be generally described as having greater oiliness than the oil itself and a slightly higher dielectric constant, generally. This agent is usually more polar than is the oil, also. The last two factors will tend to promote a concentration of the additive agent at the locale of the highest potential stresses, thus resulting in better fluid lubrication because of the superior oiliness of the additive.

Along the same lines was the gradual reduction in breakdown potential required for successive breakdowns at one setting of the equipment. This decrease was much in excess of that caused by gradual surface roughening from arcing. The actual decrease for any one setting was normally on the order of 10% after three or four breakdowns were made to occur. The decrease was very slow thereafter. Readings used for data were normally the second or third in the series. The decrease in potential required could be explained by the presence of minute quantities of water or other impurities of higher dielectric constant. Even the additive would cause this effect, as any substance of higher dielectric constant would be drawn to the region of highest electrostatic stress and require a lower breakdown potential since in these cases they also had a lower dielectric strength.

The fifth and last phenomenon was the apparent existence

of a lower limit to fluid film thickness, that is, a minimum finite thickness to which ideal fluid lubrication was maintained. Alternately this may be called a demonstration of anomalous dielectric behavior at very thin film thicknesses. Norton (15) states that ideal fluid lubrication can be maintained to about 25 microns. Needs (14) reported anomalous dielectric behavior in films below 100 microns. Bruninghaus, Watson, and Menon reported a rapid decrease in resistance to penetration in film thicknesses below 400 microns. The thinnest films measured in this investigation were approximately 50 microns. Below that region the film invariably gave the performance of an excellent conductor. It appears unlikely that enough high spots would suddenly establish contact at this thickness to give the effect of a solid conductor.

3. Conclusions and Recommendations

It is believed that the results of this investigation are valid in a qualitative way, and also valid in a relative quantitative way. That is, the quantitative results show a true trend, but the absolute values of which cannot be accurately stated owing to some contributory unknowns. To sum up, these unknowns are:

(a) Dimensions. Owing to machining tolerances which were unavoidable, some error enters into the theoretical predicted thickness and into the relation between the measured h_{ind} and h_n by capacitance method. This error largely effects the nature of agreement between theoretical and measured

values of film thickness.

(b) Leakage factor. This is a theoretical correction which leaves something to be desired. It appears obvious from various experimental investigations that the actual film thickness does not increase as quickly with the Sommerfeld Variable as theory indicates.

(c) Dielectric strength of oil at very small separations. This is a field about which more should be known. The dielectric strength used in this investigation is of rather dubious reliability owing to the necessity of extrapolating and because of the paucity of information in the region of from 50 to several hundred microns. There was too little data of undesirable inconsistency which had to be used in predicting the E_{bo} used. This question of dielectric strength could well be the subject of an extensive and exhaustive investigation in its own right. The extrapolation of the dielectric strength curve used in Appendix B was extremely dangerous in view of many writers reporting unusual and anomalous conditions in liquid dielectrics at very small separations. The consistent coincidence of experimental with theoretical values at approximately 100 microns, however, tends to dispel any fears of excessive errors in dielectric strength values used for this region.

The consistency of the experimental results with themselves is considered satisfactory. The decrease of the indicated film thickness by the breakdown method with progressive surface roughening is on the same order as that of the

increase in predominant peak to valley heights over the same period. The corresponding decrease in the capacitance thickness values is less as might be expected since this is a result of the modification of a minor portion of the capacitor area.

The utility of the two methods used bears comment. The breakdown method, while giving fairly satisfactory results, causes an undesirable physical deterioration of the surfaces involved which introduces gradually increasing relative errors that are impossible to evaluate. This characteristic alone, discounting the already mentioned difficulty of fixing the correct E_{bo} to use, makes the breakdown method a rather unsatisfactory one to employ.

The capacitance method holds good promise of being a high precision indicator of film thickness given precise instrumentation with which to work. The dielectric constant can be determined very accurately and the effective area can be settled on with satisfactory accuracy. By using a series of insulated capacitors around a portion of a bearing periphery, the location of the minimum oil film may be determined as well. This balanced bridge system across a bearing using an audio or visible alarm system to indicate unbalance furnishes the essentials of a reliable, uncomplicated, and early alarm system to supplement or supplant the present low pressure alarm system. The electrical alarm system could be balanced over the full range of satisfactory operations, could be easily applied to every important bearing, and in all

probability prevent wiping bearings completely with alert operating personnel.

A simple scheme of a visual bearing failure indicator is shown in reference 18. This system used a flashlight circuit in effect. In actual practice, one of the electrodes must be completely insulated from the rest of the machine.

As a final conclusion, the data indicate substantial support to various reports of other investigators of an anomalous dielectric behavior in the region of 50 to 100 microns film thickness. This phenomenon should be investigated further both experimentally and theoretically.

BIBLIOGRAPHY

1. Allen, C. M. The dielectric strength of oil film in plain bearings. Paper presented at wear conference at M. I. T. 16 June 1948.

2. Atkinson, R. W. High tension bridge for measuring dielectric losses in cables. Electrical Journal, February 1925.

3. Gemant, A. Liquid dielectrics. Wiley and Sons, Inc. 1933.

4. Hersey, M. D. Theory of lubrication. Wiley and Sons, Inc., 1936.

5. Hersey, M. D. Resistance, inductance, and capacitance of eccentric cylinders. Electrical World, Vol. 56, 1910, pp. 434-36.

6. Hersey, M. D. Laws of lubrication on horizontal journal bearings. American society of naval engineers, Journal, Vol. 35, 1923, pp. 648-74.

7. Hoch, E. T. Electrode effects in measurement of insulating materials. Bell System technical journal, Vol. 5, 1926, p. 555.

8. Howarth, H. A. S. Graphical study of journal lubrication. Trans. A.S.M.E., Vol. 47, 1925, pp. 1073-99.

9. Howarth, H. A. S. Character of full and partial journal bearings. Industrial engineering chemist, Vol. 18, 1926, p. 453.

10. Karelitz, G. B. Charts for studying oil film in bearings. A.S.M.E., Vol. 47, 1925, p. 1101.

11. Kluge, J. and Linckh, H. E. (In German) Piezo-electric measurement of mechanical quantities. Forschungsheft, Bd 2, Nr 5, 1931, pp. 154-65.

12. Linsley, L. J. Investigation of critical bearing pressures causing rupture in lubricating oil films. A.S.M.E. Vol. 46, 1924, pp. 855-76.

13. Miner, D. F. Insulation of electrical apparatus. McGraw-Hill Book Co., Inc., 1941.

14. Needs, S. J. Boundary film investigations. A.S.M.E. May, 1940.

15. Norton, A. E. Lubrication. McGraw-Hill, 1942.

16. Nücker, W. (In German) On the lubrication of journal bearings. Forschungsheft 352, 1932, 24 pp.

17. Poppinga, R. Wear and lubrication of piston rings and cylinders. A.S.L.E. pp. 95-106.

18. S.A.E. Journal. Bearing lubrication indicator, Vol. 24, 1929, p. 244.

19. Schering, H. and Vieweg, R. (In German) Determination of bearing lubrication by electrical measurements. Zeit. angew. chem., Bd 39, 1926, pp. 1119-23.

20. Schwaiger, A. and Sorensen, R. W. Theory of dielectrics. Wiley and Sons, Inc. 1932.

21. Stone, M. Film lubrication in sleeve bearings. Applied mechanics, Journal, Vol. 2, 1935, pp. A:59-64; Vol. 3, pp. A:31-34.

22. Tarasov, L. P. Relation of surface-roughness readings to actual surface profile. A.S.M.E., Vol. 67, 1945, p. 189.

23. U.S.N. Bureau of Ships. Lubricating oil, general information, requirements, and methods of test (N.B.S. 431). 15 Aug. 1945.

24. Whitehead, J. B. Conductivity of insulating oils. A.I.E.E. Vol. 50, 1931, pp. 692-8; Vol. 49, p. 649.

25. Whitehead, J. B. Conductivity of insulating oils under alternating current stress. Applied physics, Journal of. Vol. 11, Sept. 1940, pp. 596-603.

APPENDIX A

Table 1

$c = .002''$

Order of run	N (r.p.m.)	P" (p.s.i.)	$\mu \times 10^6$ (reyns)	$\left(\frac{r}{c}\right)^2 \frac{\mu N}{P''}$	f	E_b (volts)	h_n (microns) Dielect.	Cap.	Theor.	Remarks
1	241	42.2	28.7	41.1	.0370	62	225	227	1040	(New
3	"	190	21.7	6.9	.0107	31	113	154	460	(journal
2	"	338	21.7	3.87	.0083	29	106	148	320	(being
5	"	485	17.65	2.19	.0059	26	94	133	210	(worn
7	"	558	16.1	1.74	.0051	24	87	125	174	(in.
4	"	632	17.35	1.66	.0056	23	84	118	168	(Bearing
8	"	781	16.75	1.30	.0048	20	73	108	138	(Somewhat
6	"	928	14.85	.97	.0048	17	62	104	106	(pitted at
										(start
1	144	42.2	23.7	20.2	.0151	42	153	190	820	
3	"	190	23.7	4.5	.0089	25	91	140	356	
2	"	338	23.7	2.52	.00645	20	73	130	238	
5	"	485	21.7	1.61	.0054	18.5	67	112	166	
4	"	632	21.4	1.22	.0052	15	54	108	130	
7	"	781	21.7	1.0	-	-	-	-	110	(Mech.
6	"	928	-	-	-	-	-	-	-	(breakdown
										(indicated

APPENDIX A

Table 2

$c = .00475"$

Order of run	N (r.p.m.)	P" (p.s.i.)	$\mu \times 10^6$ (reyns)	$\left(\frac{r}{c}\right)^2 \frac{\mu N}{P"}$	f	E_b (Volts)	h_m (microns) Dielect.	Cap.	Theor.	Remarks
8	362	116	13.95	1.93	.0064	70	255	193	458	New
3	"	190	17.05	1.44	.0062	69	251	168	360	bearing
1	"	337	17.65	.84	.0061	53	193	160	215	in
4	"	484	16.3	.54	.0048	34	123	142	140	use
6	"	560	13.9	.40	.0043	29	105	128	100	
2	"	632	15.1	.38	.00505	25	91	118	95	
5	"	780	13.5	.28	.00434	19	69	104	75	
7	"	853	10.7	.20	.0041	14	51	96	50	
9	"	928	13.0	.22	.0043	-	-	-	-	Breakdown of film indicated
5	193	116	19.45	1.43	.0067	58	211	168	355	
3	"	190	19.45	.873	.0059	52	189	135	225	
1	"	337	19.45	.492	.00515	34	123	126	130	
4	"	484	18.60	.328	.0045	25	91	117	88	
2	"	632	19.45	.263	.0045	17	62	104	70	
6	"	707	17.05	.206	.0042	12	44	93	55	
3	345	116	20.8	2.74	.00954	65	236	186	595	
1	280	"	22.2	2.37	.00912	63	229	174	530	
8	237	"	20.1	1.82	.0078	62	225	167	438	
2	200	"	23.0	1.76	.0075	56	203	154	425	
4	141	"	19.7	1.06	.0055	36	131	138	272	
5	108	"	20.8	.86	.0053	33	120	126	220	
6	79	"	23.0	.69	.0049	23	84	111	180	
7	64	"	23.5	.575	.0049	20	73	99	150	

APPENDIX A

Table 3

$c = .00475''$

Order of run	N (r.p.m.)	P" (p.s.i.)	$\mu \times 10^6$ (reyns)	$\left(\frac{r}{c}\right)^2 \frac{\mu N}{P''}$	f	E_b (volts)	h_n (microns) Dielect.	Cap.	Theor.	Remarks
4	367	338	13.20	.634	.0070	38.5	140	108	165	New
3	315	"	13.95	.576	.0072	35.0	127	105	150	journal
2	266	"	15.14	.527	.0074	29.5	107	103	138	in
1	220	"	15.14	.437	.0069	24.0	87	93	116	use
1	375	338	14.9	.732	.0068			111	198	New
5	362	"	12.2	.577	.0058			114	154	bearing
6	304	"	12.25	.487	.0055			107	126	and
3	250	"	14.4	.470	.0055			105	122	journal
2	200	"	14.85	.390	.0053			99	97	in
7	163	"	17.05	.364	.0048			91	89	use
4	156	"	16.75	.343	.0049			91	83	
8	146	"	17.65	.337	.0047			96	81	
9	118	"	19.7	.305	.0045			87	74	
10	98	"	20.8	.267	.0046			82	64	
11	76	"	22.9	.228	.0040			77	54	
12	58	"	24.3	.185	--			-	44	Breakdown indicated

APPENDIX B

Table 4

Dielectric Strength Test of 2190T Oil

Cup No.	Electrode Spacing (inches)	E_b(KV)	E_{bo}(KV/in)	E_{bo}(ave.) for spacing
1	.1	30.0		
		33.7		
		26.0		
		25.4		
		23.6		
		Ave. 27.74	277.4	
2	.1	39.6		
		31.5		
		40.0		
		33.6		
		33.6		
		Ave. 35.66	356.6	
3	.1	36.0		
		35.4		
		39.0		
		42.3		
		32.7		
		Ave. 37.08	370.8	334.9
4	.025	7.6		
		8.0		
		7.1		
		8.8		
		10.05		
		Ave. 8.32	332.8	
5	.025	8.7		
		9.8		
		9.9		
		10.7		
		11.9		
		Ave. 10.2	408	370.4
6	.00983	2.1		
		2.5		
		2.5		
		2.5		
		2.4		
		Ave. 2.4	244	

APPENDIX B

Table 4
(Continued)

Cup No.	Electrode Spacing (inches)		E_b (KV)	E_{bo}(KV/in)	E_{bo}(ave.) for spacing
7	.0102		4.30		
			3.95		
			3.50		
			4.30		
			4.90		
		Ave.	4.19	412	
8	.009		2.1		
			2.2		
			2.6		
			2.4		
			2.6		
		Ave.	2.38	265	307
9	.003		.90		
			1.10		
			.75		
			.75		
			.80		
		Ave.	.86	287	287

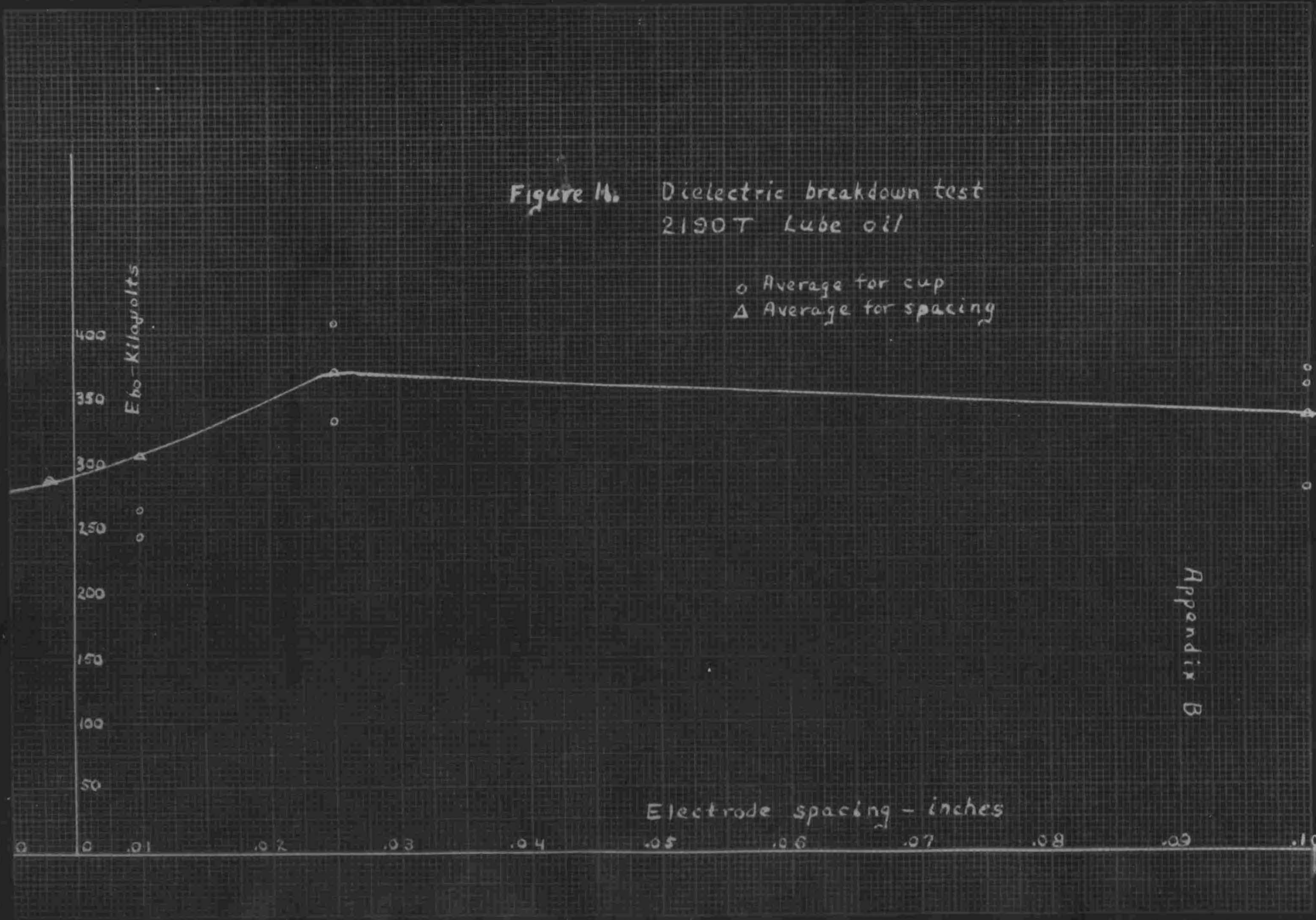


Figure 14. Dielectric breakdown test
2190T Lube oil
o Average for cup
Δ Average for spacing
Ebo-Kilovolts
400
350
300
250
200
150
100
50
Electrode spacing - inches
0
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
Appendix B

Appendix B

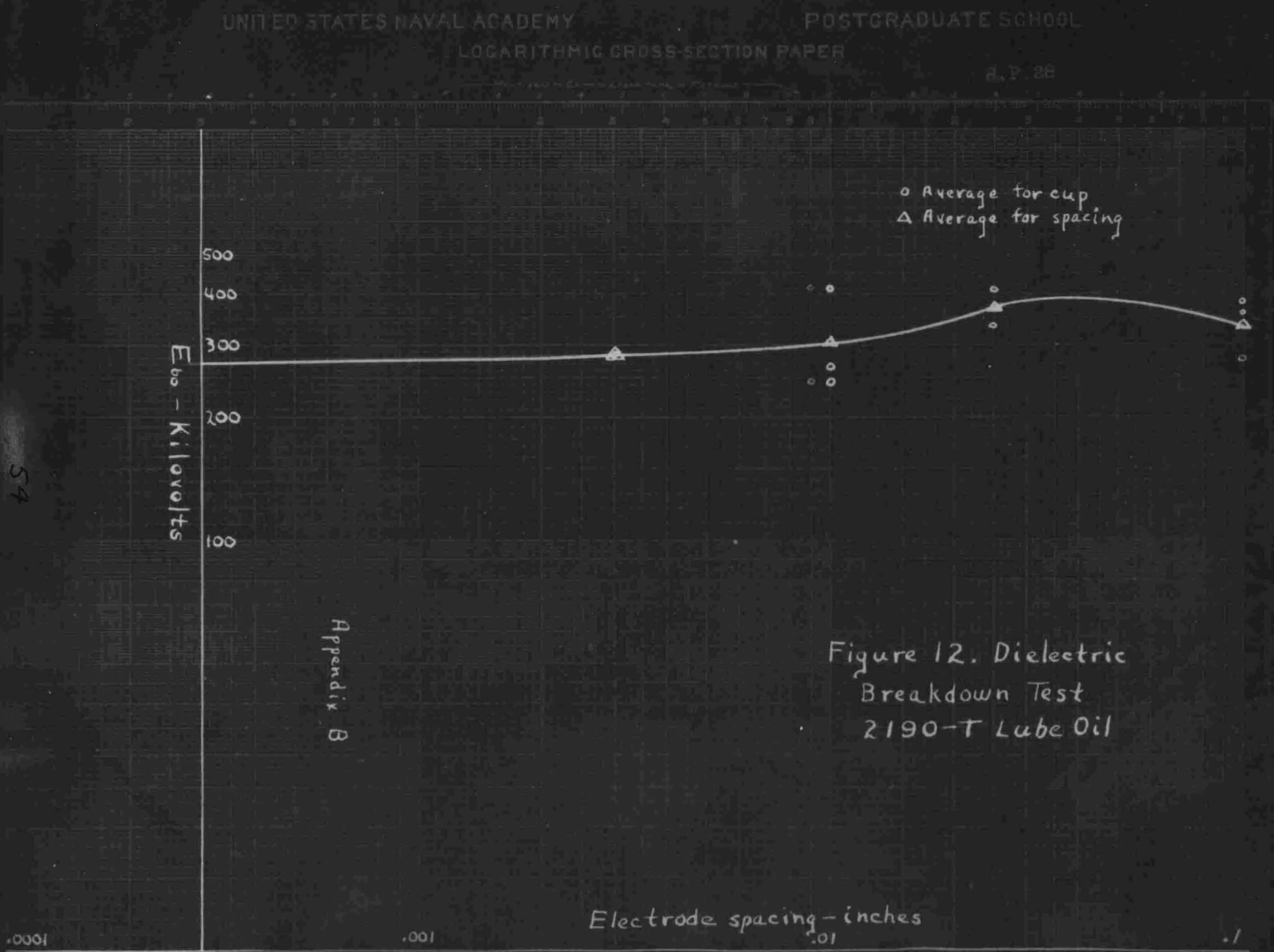


Figure 12. Dielectric Breakdown Test 2190-T Lube Oil

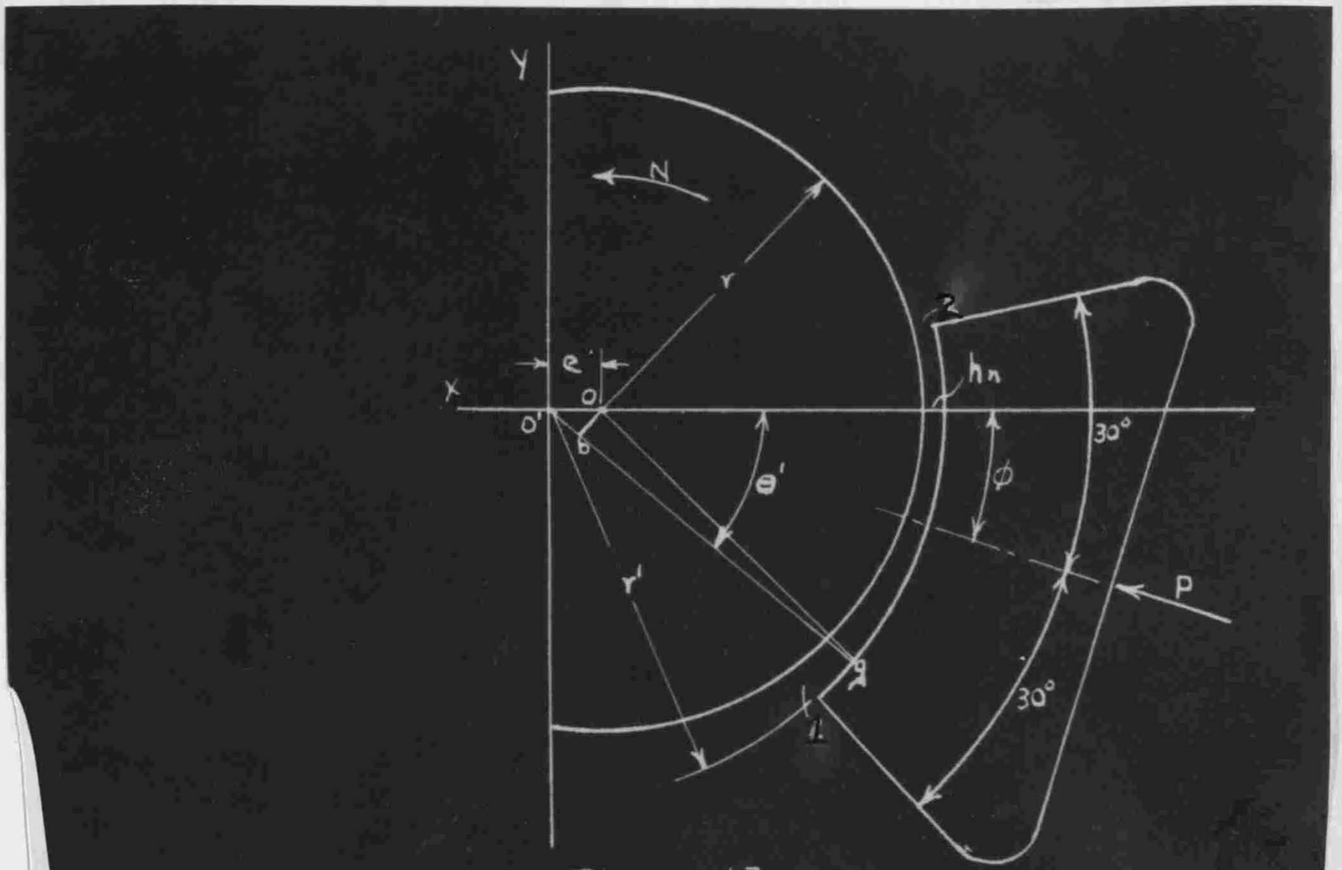


Figure 13.

Relation Between Average and Minimum Film Thickness

For parallel plates, the expression for capacitance is

$$C = \frac{2.54\ KA}{4\pi 9 \times 10^5 h} \text{ microfarads}$$

with dimensions in inches.

Since in the case above, the plates are not parallel, we must integrate, using an infinitesimal amount of area dA as the basis, in which case we may assume parallel plates.

We will assume unit axial length. Then

$$dC \doteq \frac{2.54K\, dA}{4\pi\, 9\times 10^5 h} \tag{1}$$

Now assuming the average radius of the dielectric from point O', the origin, to be

$$\frac{r' + r + e}{2} \tag{2}$$

which is very nearly true, then

$$dA = \frac{r' + r + e}{2}\, d\theta' \tag{3}$$

Also

$$h_n = r' - (r + e) \tag{4}$$

As a further close approximation we may say that

$$h \cong r' - (r + e \cos\theta')$$

or

$$\cong e\left(\frac{r' - r}{e} - \cos\theta'\right), \tag{5}$$

this being inaccurate by the amount that gO exceeds gb (Refer to Figure 13). In our case this is extremely small since Ob approaches as a maximum something less than .4 of one percent of gO. Using these approximations then, to save much tedious detail, we arrive at the expression

$$dC \cong \frac{2.54\, K\, \frac{r' + r + e}{2}\, d\theta'}{e\left(\frac{r' - r}{e} - \cos\theta'\right)\left(4\pi\, 9\times 10^5\right)} \tag{6}$$

then

$$C \cong \frac{2.54\, K\, (r' + r + e)}{9\times 10^5 \times 2e \cdot 4\pi}\left[\int_{\theta_1'}^{\theta_2'} \frac{d\theta'}{\frac{r' - r}{e} - \cos\theta'}\right. \tag{7}$$

$$\cong \frac{2K_1}{\sqrt{a^2-b^2}} \left| \tan^{-1}\left[\frac{\sqrt{a^2-b^2}}{a+b} \tan\frac{\theta'}{2}\right] \right|_{\theta_1'}^{\theta_2'} \tag{8}$$

where

$$a = \frac{r'-r}{e} = \frac{c}{e} \qquad K_1 = \frac{2.54\,K\,(r'+r+e)}{4\pi\, 9 \times 10^5 \cdot 2e}$$

$$b = -1$$

Now we are ready to compute the values of C for various values of e. For these computations we must use the theoretical values of ϕ determined from Figure 2 in connection with the theoretical thicknesses, using the Sommerfeld Variable as the entering parameter. For c of .002" we found from Figure 2 that in the range of variable covered ϕ changes only from 16.°5 to approximately 19.°5. Hence we may again cut down the tedium by assuming ϕ constant at 18°, with negligible error. This results in θ_2' of 12° and θ_1' of 48°. Similarly, an average ϕ for c of .00475" is 16.°5, resulting in $\theta_2' = 13.°5$ and $\theta_1' = 46.°5$. Tables 5 and 6 show the results of the integrations using a series of assumed values for h_n.

The last column of Tables 5 and 6 shows the indicated thickness, h_{ind}, arrived at by using the known area of the plates (i.e. bearing surface) and the computed capacitance in solving the relation

$$h_{ind} = \frac{2.54K\,A}{4\pi 9_x 10^5\,C}$$

Figure 14 shows the curve relating h_n to h_{ind} , from which the experimental values of thickness, h_n , by the capacitance method were derived, after entering this chart with h_{ind} obtained from the measured capacitance.

APPENDIX C

Table 5

$\phi_{ave} = 18^{\circ}$ $\theta_2' = 12^{\circ}$ $\theta_1' = 48^{\circ}$ $c = .002''$

h_n (microns)	e (microns)	a	$\sqrt{a^2-b^2}$	$\frac{2}{\sqrt{a^2-b^2}}$	$\frac{\sqrt{a^2-b^2}}{a+b}$	$\tan_2^{-1}$ (rad.)	$\tan_1^{-1}$ (rad.)	$K_1 \times 10^7$	$C \times 10^5$	h_{ind} (microns)
50	1950	1.0256	.2278	8.78	8.88	.751	1.323	2634	486	105
100	1900	1.0526	.3286	6.09	6.24	.581	1.225	2703	298	172
150	1850	1.0811	.4107	4.87	5.07	.490	1.153	2770	222	231
200	1800	1.1111	.4844	4.13	4.36	.429	1.095	2850	180	285
250	1750	1.1429	.5533	3.62	3.87	.386	1.043	2930	151	340
300	1700	1.1765	.6198	3.23	3.51	.354	1.00	3020	132	389

Table 6

$\phi_{ave} = 16.^{\circ}5$ $\theta_2' = 13.^{\circ}5$ $\theta_1' = 46.^{\circ}5$ $c = .00475''$

h_n (microns)	e (microns)	a	$\sqrt{a^2-b^2}$	$\frac{2}{\sqrt{a^2-b^2}}$	$\frac{\sqrt{a^2-b^2}}{a+b}$	$\tan_2^{-1}$ (rad.)	$\tan_1^{-1}$ (rad.)	$K_1 \times 10^7$	$C \times 10^5$	h_{ind} (microns)
50	4700	1.0106	.1463	13.67	13.75	1.02	1.40	1096	362	142
100	4650	1.0215	.2086	9.59	9.70	.856	1.33	1106	232	221
150	4600	1.0326	.2575	7.77	7.90	.752	1.28	1120	177	290
200	4550	1.0440	.2997	6.67	6.82	.679	1.24	1130	145	354
250	4500	1.0555	.3379	5.92	6.08	.625	1.20	1142	124	414
300	4450	1.0674	.3734	5.36	5.54	.581	1.175	1156	109	470